Customized Corneal Ablation
The Quest for SuperVision

Scott M. MacRae, MD
University of Rochester Medical Center
Rochester, New York

Ronald R. Krueger, MD, MSE
Cole Eye Institute
Cleveland Clinic Foundation
Cleveland, Ohio

Raymond A. Applegate, OD, PhD
University of Texas Health Science Center
San Antonio, Texas

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Chapter Five

Physics of Customized Corneal Ablation

David Huang, MD, PhD

INTRODUCTION

In a broad sense, refractive surgeons are performing customized corneal ablation today. After all, we do not apply the same laser ablation to every eye. Each ablation in laser-assisted in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK) is tailored to the eye's subjective spherocylindrical refraction. Our current usage of the term "custom cornea," however, refers specifically to laser ablation of the cornea customized to each eye's higher-order as well as spherocylindrical aberrations. Eliminating higher-order aberrations may allow us to achieve a supranormal vision ("20/10 perfect vision"). Reduction of higher-order aberrations is also useful in restoring vision to a normal level in pathologic conditions such as corneal scar, ectasia, and complicated keratorefractive surgery. In either case, customized corneal ablation requires more precision in all aspects of the surgery. More precise control of laser ablation is required. Novel wavefront sensors are needed to precisely map the aberrations of the eye. Accurate alignment of laser ablation with either a wavefront or corneal topographic map is also necessary.

In order to use, evaluate, and improve the "custom cornea," the ophthalmic surgeon needs to understand the physical principles behind the technology. This introductory chapter will cover these principles in broad terms.

WHY, WHAT, AND HOW OF WAVEFRONT OPTICS

Why Wavefront?

In order to achieve super normal vision, it is essential to correct the wavefront aberration of the entire optical system of the eye. If one only corrects corneal topographic aberration, vision would still be limited by aberrations in the posterior corneal surface, the crystalline lens, and the remaining refractive elements in the eye.

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What is a Wavefront?

Wavefront optics is not a familiar subject to most people outside of the field of optical engineering and physics. In this introductory chapter, we start with a graphic explanation of wavefront. A more comprehensive treatment of the subject can be found in Chapter Six.

Light is a traveling electromagnetic wave. A wavefront is a continuous isophase surface. To simplify our mental picture from three to two dimensions,

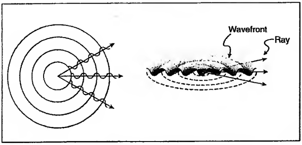

Figure 5-1. The relationship between wavefront and rays in a surface wave example.

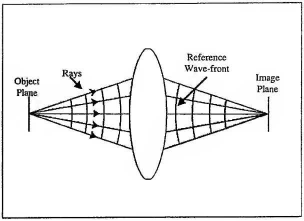

Figure 5-2. An ideal optical system. Light from the object plane is focused by the lens and converges at the image plane. Deviation from the ideal wavefront defines aberration.

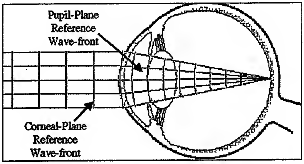

Figure 5-3. An ideal eye. Deviation from the ideal wavefront defines aberration.

let's first consider waves on the surface of water. Imagine throwing a stone into still water and observing the expanding circles of waves. If we take a snapshot of this wave at one point in time (Figure 5-1), we can draw circular wavefronts across the crests (phase 0) of the waves. We can also draw the wavefronts at any arbitrary reference phase, such as the troughs (phase π), or the midpoint of descent (phase $\pi/2$). Note that the wavefronts are perpendicular to the direction of travel, which can be represented by rays (see Figure 5-1). For optical waves, there is one more dimension, and a wavefront is a surface instead of a line.

Both wavefronts and rays can be used to describe wave propagation. For example (Figure 5-2), an optical wavefront from a point source propagates through a lens. As the wave travels through the lens, the speed of propagation is slowed because the lens

> As the wave travels through the lens, the speed of propagation is slowed because the lens material has a higher index.

material has a higher index of refraction than the optical media surrounding it (generally air). The center of the lens is thicker and therefore retards the center of the wavefront relative to the periphery. The differential slowing imparted by the shape of the convex lens in air converts the incoming diverging (convex) wavefront into a converging (concave) wavefront on exit (see Figure 5-2). In the absence of aberration, wavefront converges to a diffraction-limited spot at the focus. Wavefront aberration is defined by the deviation of the actual wavefront from an ideal reference wavefront that is centered on the focus (see Figures 5-2 and 5-3)

The propagation can also be described by ray optics. Recall that rays are at all points perpendicular to the wavefront. At the lens surfaces, the incoming diverging rays are refracted according to Snell's law at each lens location and, again, converge toward the focus. The deviation of the rays from the perfect focus ray path can be used to derive the wavefront aberration.

How is Wavefront Aberration Used to Guide Corneal Ablation?

Wavefront aberration can be corrected at a number of locations in the eye. If one were to implement the correction by inserting an intraocular lens (IOL) implant, then the correction should be guided by the wavefront aberration at the plane of the lens implant (see Figure 5-3). For customized corneal ablation, the ablation pattern is derived from the wavefront aberration at the corneal plane. Defining ocular aberration by the wavefront just outside the eye follows the

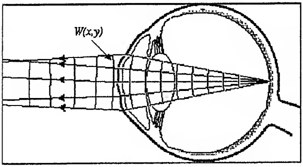

Figure 5-4. Wavefront aberration exiting the eye from a foveal point source.

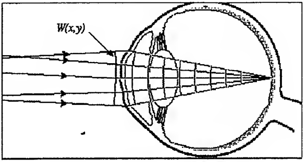

Figure 5-5. Entrance wavefront needed to nullify ocular aberrations.

convention of Smirnov.[1] Most references follow the Howland convention,[2-4] which defines ocular aberration by the wavefront at the pupil plane (see Figure 5-3). Because the corneal plane is not far from the pupil plane, measurements of W(x,y) at the two planes produce similar results. They can be interconverted by calculations that assume a standard optical model of the eye.

Wavefront aberration of the eye is defined as the deviation of the actual wavefront from an ideal reference wavefront emanating from a foveal point source. For an eye focused at infinity, the ideal wavefront exiting the aberration-free eye is a flat plane (see Figure 5-3). In a real eye, there are optical aberrations, and the exit wavefront deviates from that of the plane wave (Figure 5-4). This wavefront aberration is W(x,y), where x and y are the horizontal and vertical axes. W(x,y) is conventionally measured in microns.

Now we reverse the direction of propagation and watch W(x,y) enter the eye (Figure 5-5). By symmetry, we can see that W(x,y) will perfectly cancel out

Diffraction of light limits the size of the focussed spot even in the absence of optical aberration. The diffraction limit depends on the wavelength and numerical aperture.

ocular aberrations and focus to a point (strictly speaking, a diffraction-limited spot) at the fovea. Diffraction of light limits the size of the focussed spot even in the absence of optical aberration. The diffraction limit depends on the wavelength and numerical aperture. In order for a point source from infinity to achieve perfect focus in this aberrated eye, we need a lens at the corneal surface that converts the flat wavefront to W(x,y). This lens can be etched onto the corneal surface by customized ablation. Removal of 1 micron of corneal tissue reduces wavefront retardation by ncornea - nair microns. Therefore, the equation for the customized corneal ablation depth A(x,y) needed to correct ocular wavefront aberration W(x,y) is (equation 1):

$$A(x,y) \times (n_{cornea} - n_{air}) = C - W(x,y)$$

where n_{cornea} = corneal index of refraction, n_{air} = refractive index of air, and C is the smallest constant depth needed to keep A(x,y) from becoming negative anywhere. Ablation depth A(x,y) cannot take on a negative value because ablation cannot add tissue to the cornea. C = the maximum value of W(x,y) over the optical zone.

Equation 1 is a basic starting point for designing wavefront-guided ablation. A more comprehensive treatment of the subject is found in Chapter Eight. As with the Munnerlyn formula for spherocylindrical ablation, equation 1 ignores the eye's response to laser ablation. In the context of PRK, Munnerlyn describes this simplifying assumption very well in his classic paper[5]: "The following analysis assumes that if an area of the epithelium is removed and a portion of the stroma is ablated, the epithelium will regrow with a uniform thickness and produce a new corneal curvature determined by the new curvature of the stroma."

Reality differs from this assumption and modification of the corneal surface does occur after both PRK and LASIK.[6,7] To realize the full potential of custom cornea, we will eventually need to understand and deal with the corneal biological response. Biomechanical changes are part of the corneal response and are discussed in Chapter Nine.